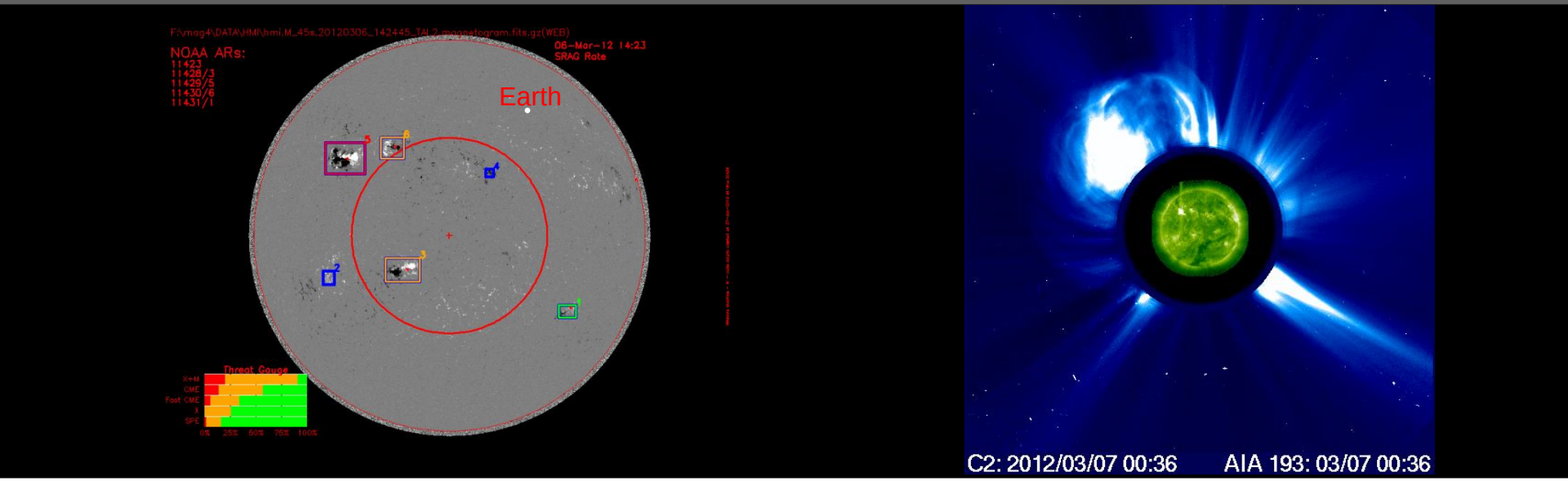
National Aeronautics and Space Administration

SCIENCE & TECHNOLOGY OFFICE



Forecasting Geoeffective CMEs

David Falconer

September 20, 2016

Alabama Power Grid Defense Conference 2016

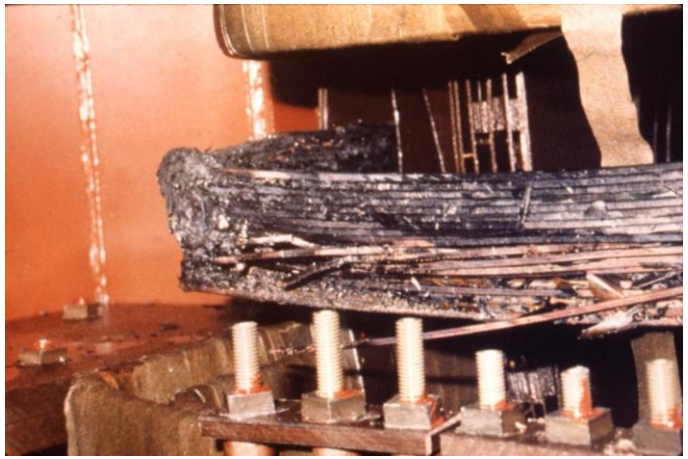
Catastrophic Damage: A Modern Carrington Level Event

Lesser Event

Major Damage

"This image shows heating related damage to the current carrying windings of the transformer. To provide cooling for normal operations, the coils are immersed in an oil-bath. As you can see, an oil-bath does not cool well enough to protect against the GIC."

Damaged Power Station Transformer

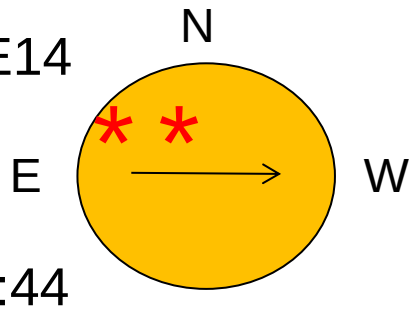


March 1989 Quebec Blackout

On March 13, 1989 the entire province of Quebec, Canada suffered an electrical power blackout.

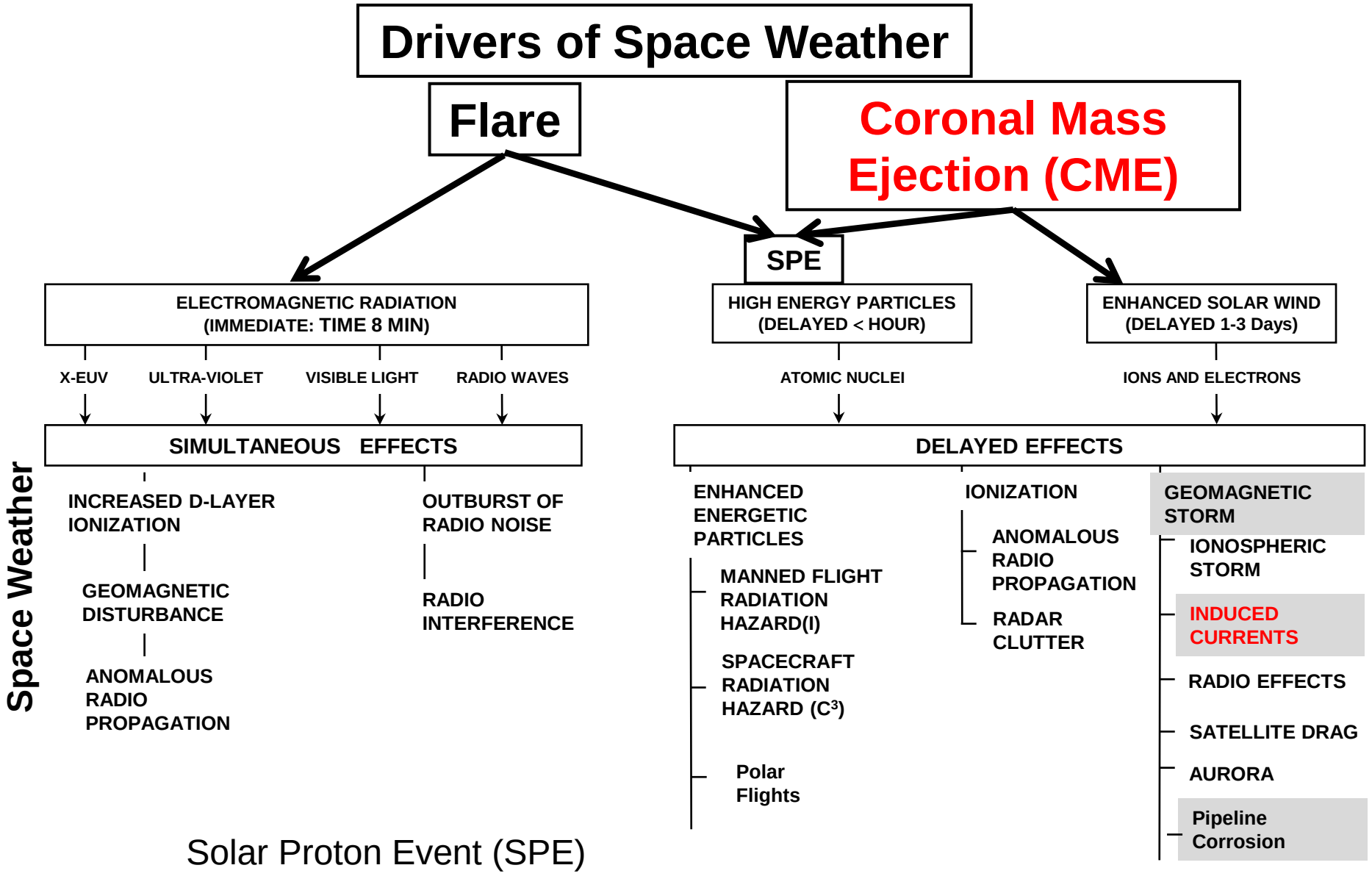
March 1989 Quebec Blackout

- AR 5395 produced on March 6, 14UT a X15 flare N35E69
- March 10 18UT a X4.5 flare N35E14
- Geomagnetic event starts on March 12.
- Reaches a DST -589 on March 13 1UT
  - largest DST magnitude in last 50 years. March 13, 7:44 UT Quebec Blackout



"On the evening of Monday, March 12 the vast cloud of solar plasma (a gas of electrically charged particles) finally struck Earth's magnetic field. The violence of this 'geomagnetic storm' caused spectacular **'northern lights' that could be seen as far south as Florida and Cuba**. The magnetic disturbance was incredibly intense. It actually created electrical currents in the ground beneath much of North America. Just after 2:44 a.m. on March 13, the currents found a weakness in the electrical power grid of Quebec. In less than 2 minutes, the entire Quebec power grid lost power." ***Dr. Sten Odenwald***

Space Weather Overview



Solar Proton Event (SPE)

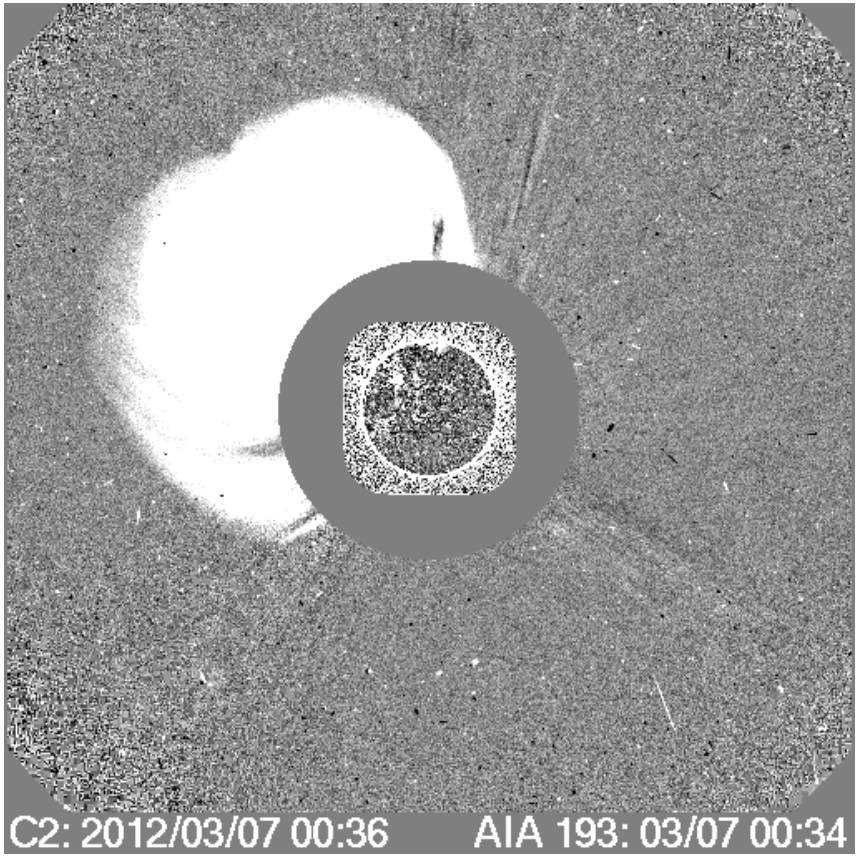
The Solar Threat to the Power Grid

Geomagnetic Storm

- Powerful CME
- Earthward Directed
- Strong Coupling with Earth Magnetosphere

Threat to Local Power Grid

- Magnetic Latitude (high latitude most at risk)
- Magnetic Longitude
- Local Geology
- Power Grid



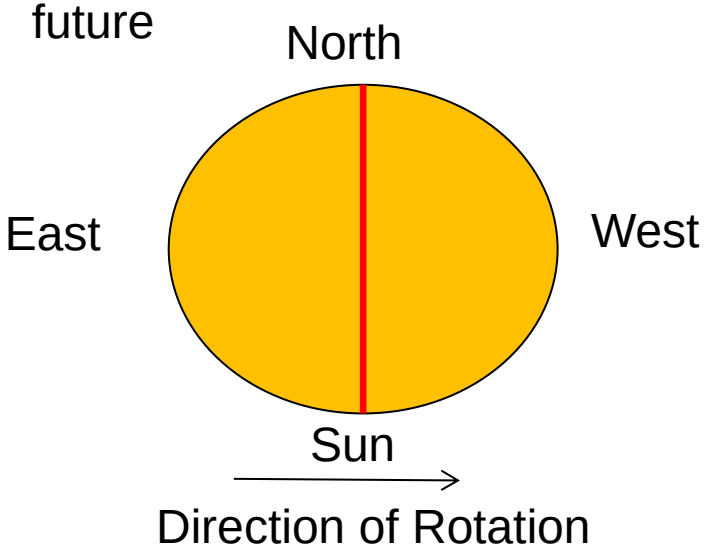
“Perfect” Storm

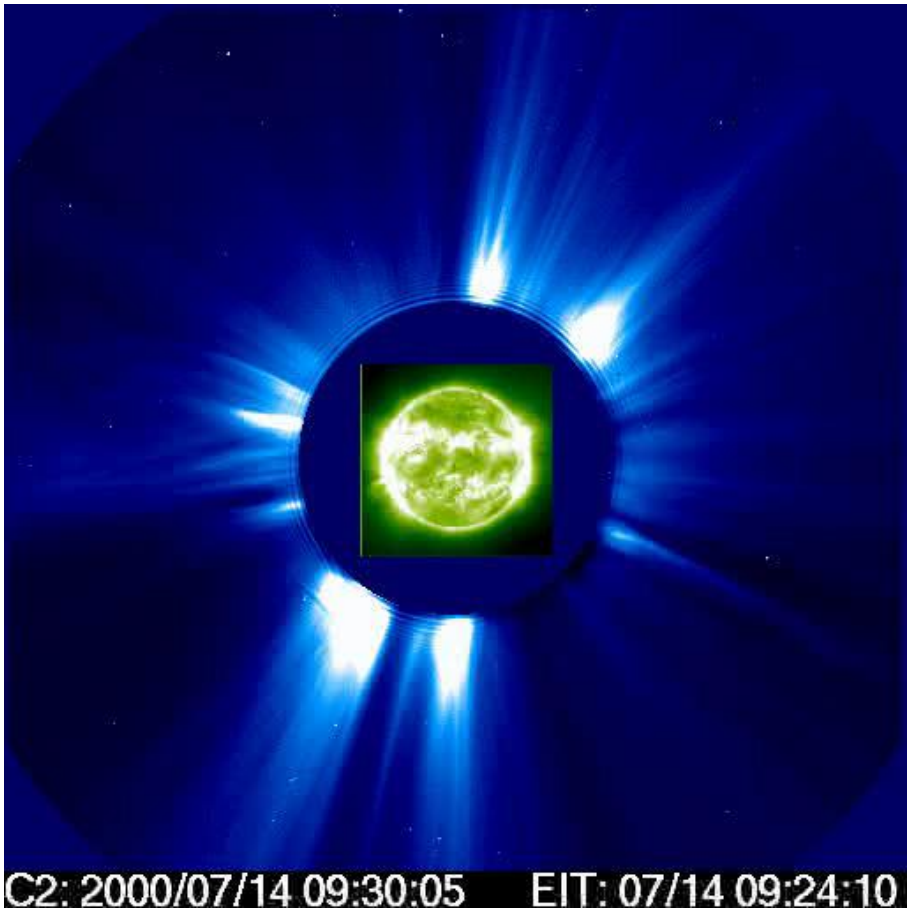
The CME needs to be Earthward Directed

CMEs that are not directed toward to Earth cannot cause geomagnetic storms on Earth

Active regions near disk center are dangerous

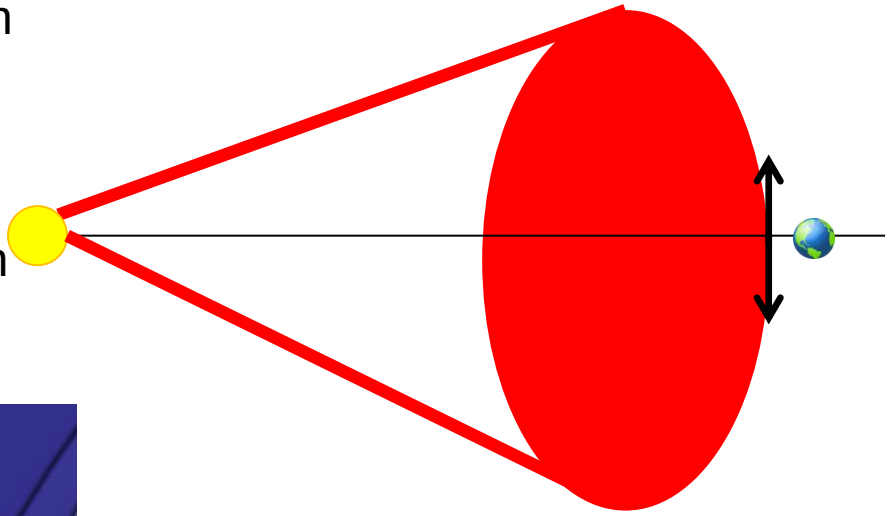
Active regions to the left of disk center (East) will be a threat in future



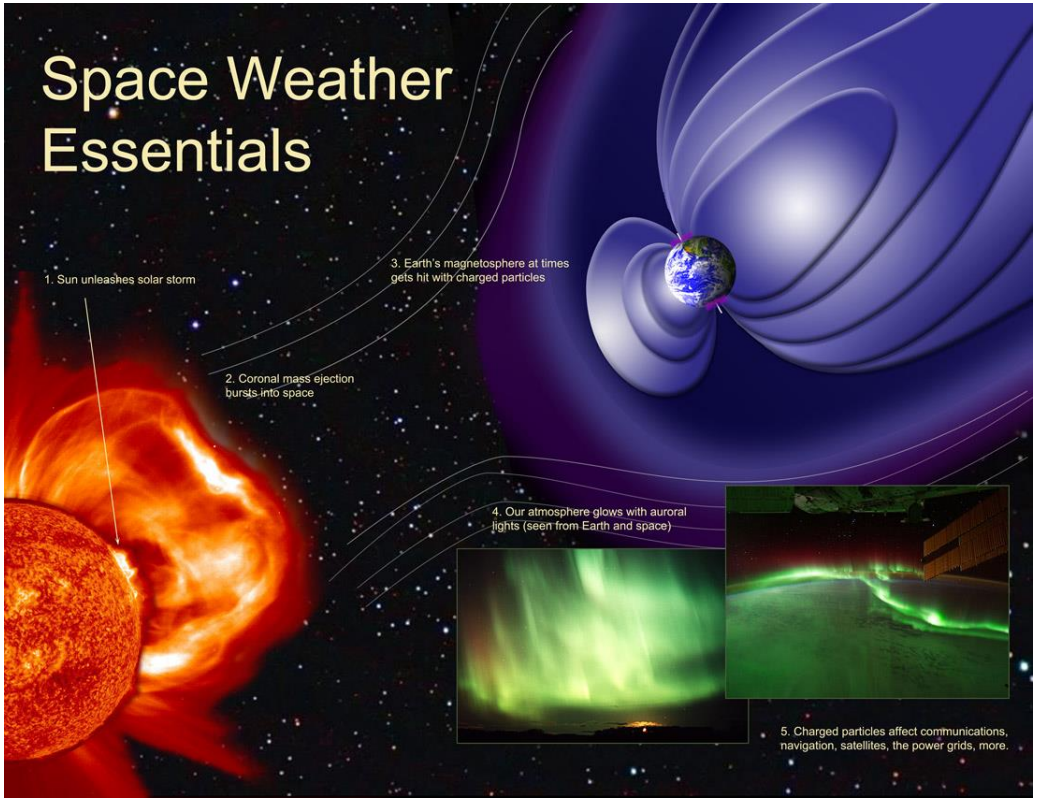


Magnetic Coupling

- Magnetic coupling is the strongest when the vertical component the CME's magnetic field is directed southward
- The direction is only known as CME passes ACE at L1 position, where it can be measured (1% of the distance from the Sun to the Earth)



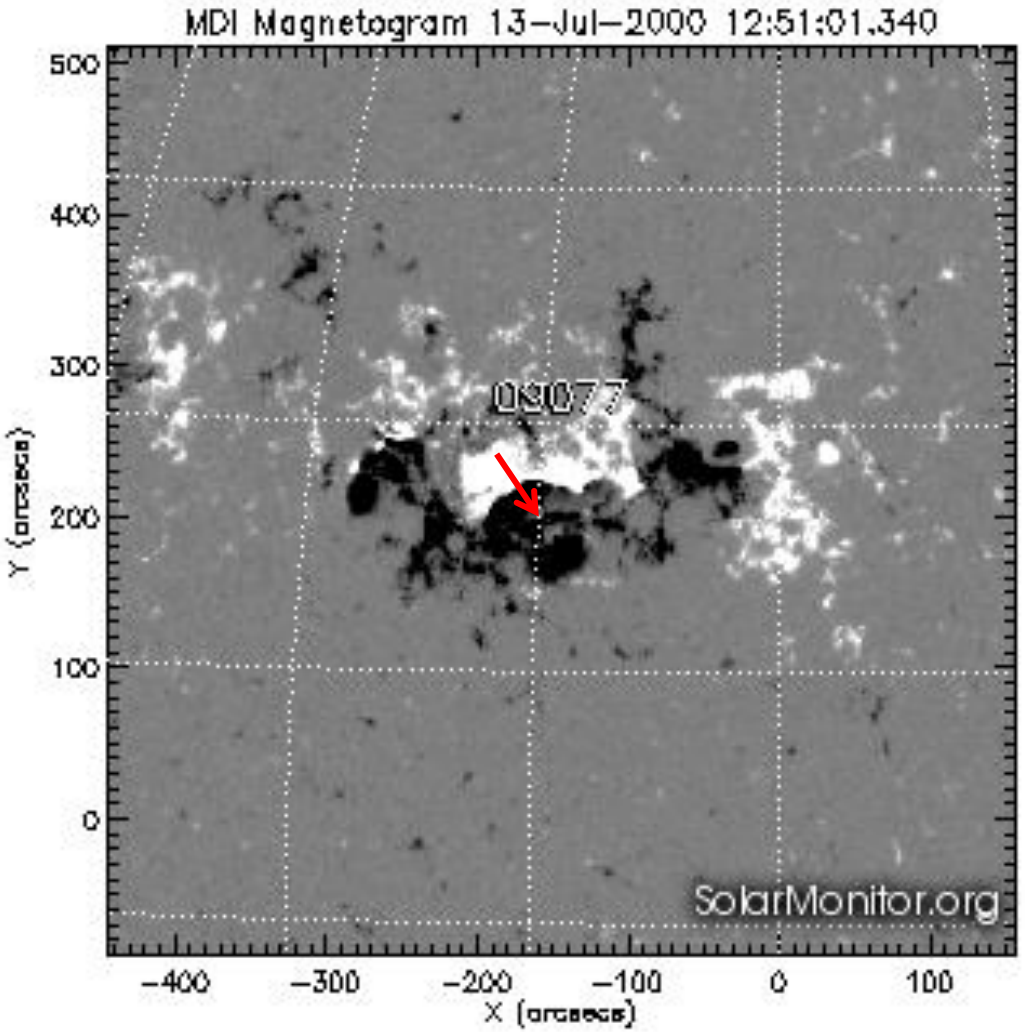
Earth, Sun not to Scale



Not to Scale
Credit: NASA

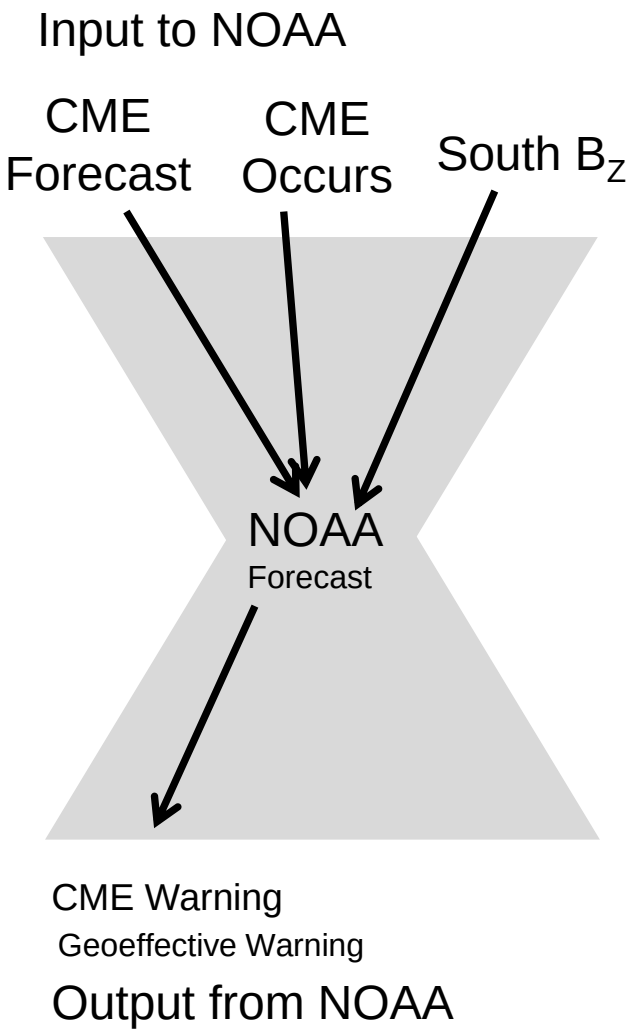
Forecasting Leading Edge Magnetic Field

- There is a loose correlation between the overarching magnetic field, and the leading edge magnetic field
- Work is being done to improve the forecasting
- Gives more warning for severe geomagnetic storm
- Not yet ready for Research to Operations (R2O), much less Operations



Forecasting Overview

- Watch
  - A threatening active region is rotating toward or is near disk center
  - In most cases, except for a rapidly emerging active region, this gives several days of notice
- Warning
  - An active region near disk center has produced a large flare and a fast CME
  - ~24-48 hours of notice, the faster more dangerous ones, less time
- Good magnetic coupling
  - ACE is at 0.99 AU (Earth at 1 AU), warnings of order of tens of mintues

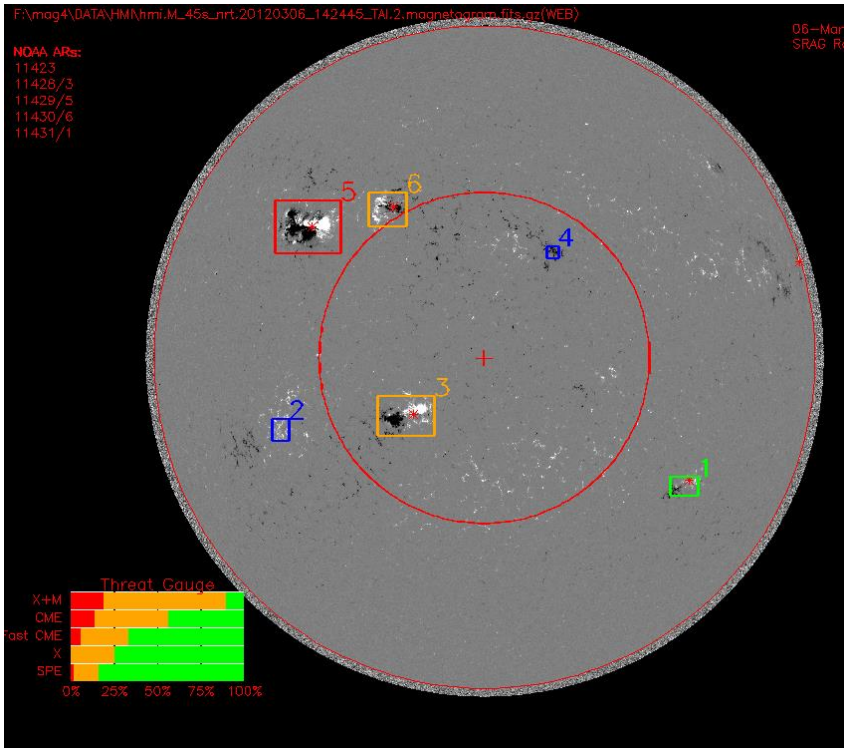


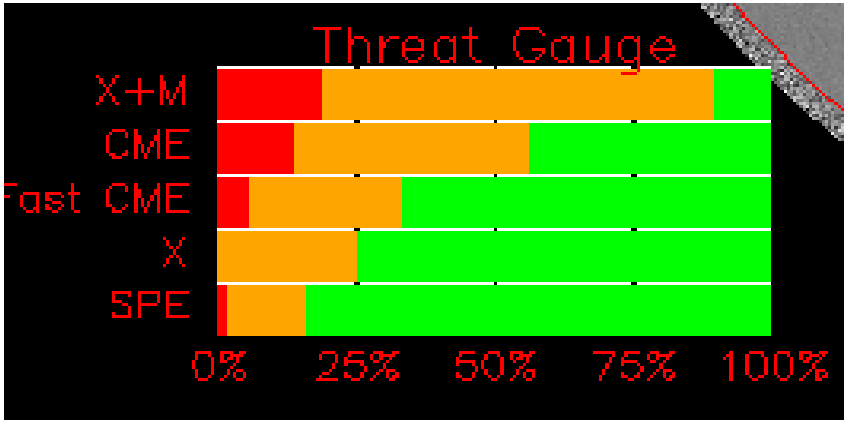
NOAA/SWPC does the day to day forecasting
http://www.swpc.noaa.gov/

Identification of Threatening Active Regions

MAG4 CME Forecast of Fast CME

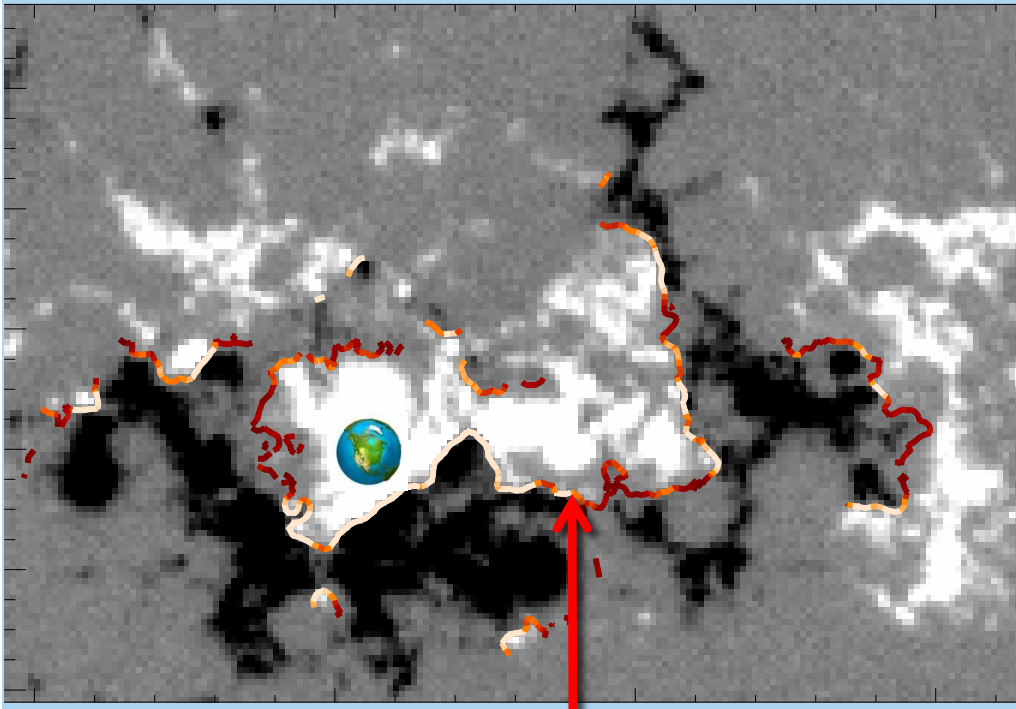
- Coronal Mass Ejections (**CMEs**), like earthquakes are very difficult to predict
- Correct answer most of the time is No! (Useless forecast)
- Historical records can provide empirical base forecasts
- MAG4 (Magnetogram Forecast) uses empirical data to predict the event rate of dangerous solar activity
- It does this automatically 24/7, making new forecasts every 96 minutes
- It forecasts **major flares**, **CMEs**, and Solar Proton Events (**SPEs**)





MAG4 Science

- Flares and CMEs are powered by magnetic energy stored in the chromosphere and corona
- Direct measurements of coronal magnetic energy are inaccurate
- When the magnetic field is stressed, the more energy is stored and available for “explosive release”; more energy is stored, greater the chance of a major flare
- MAG4 uses a proxy to quantify the free energy stored in an active region
- Event rates are correlated with the magnitude of the free-magnetic-energy proxies



Neutral Line, color coded for gradient

500 G

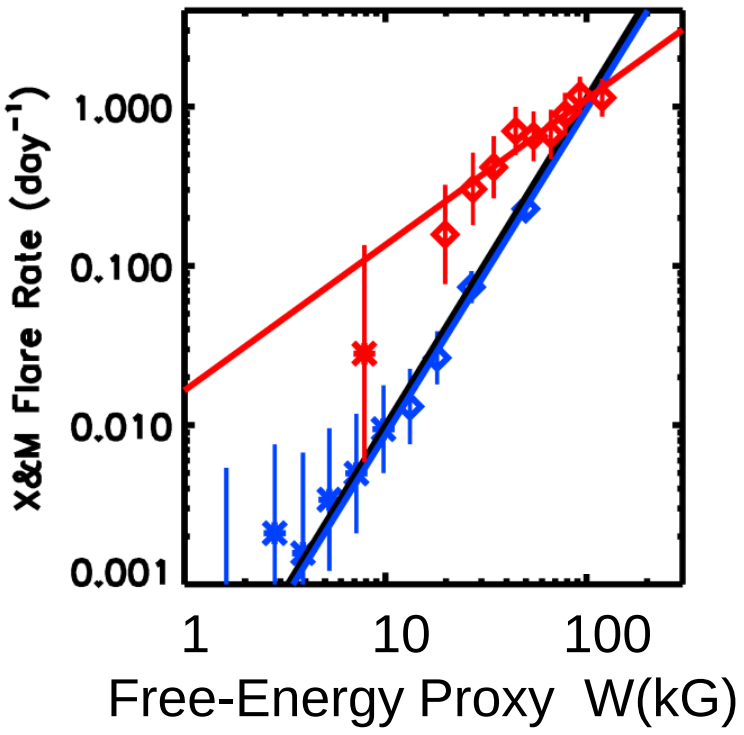
-500 G

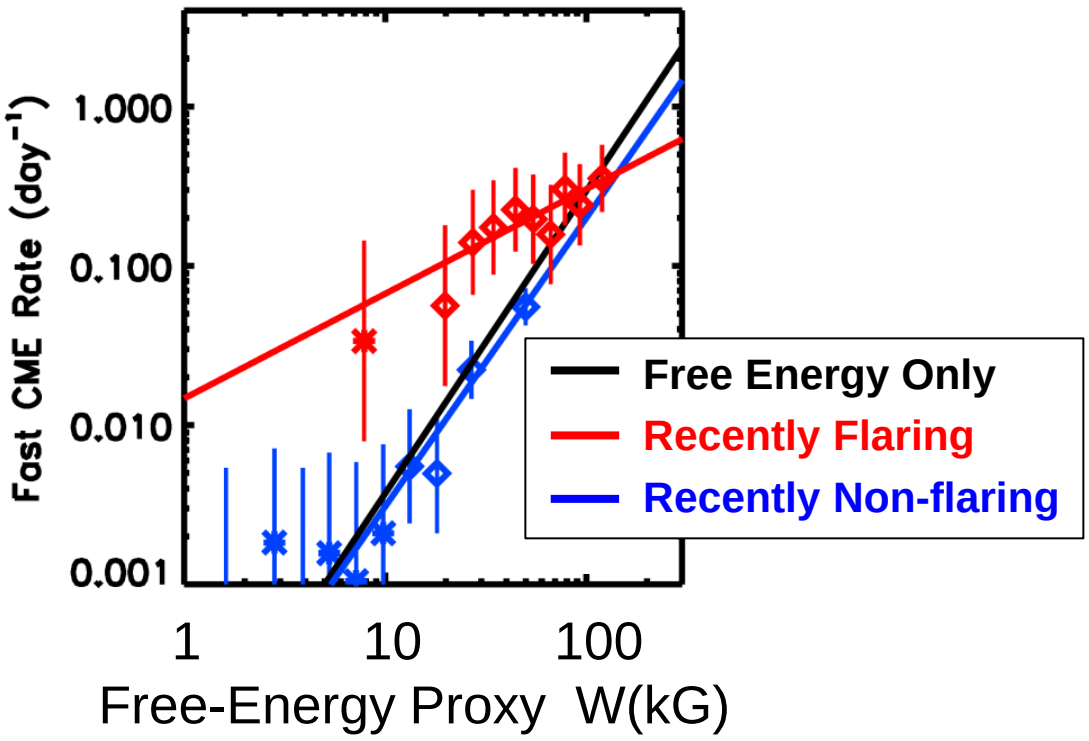
0.1G/km

0 G/km

Earth magnetic field 1 G

Forecast Curves

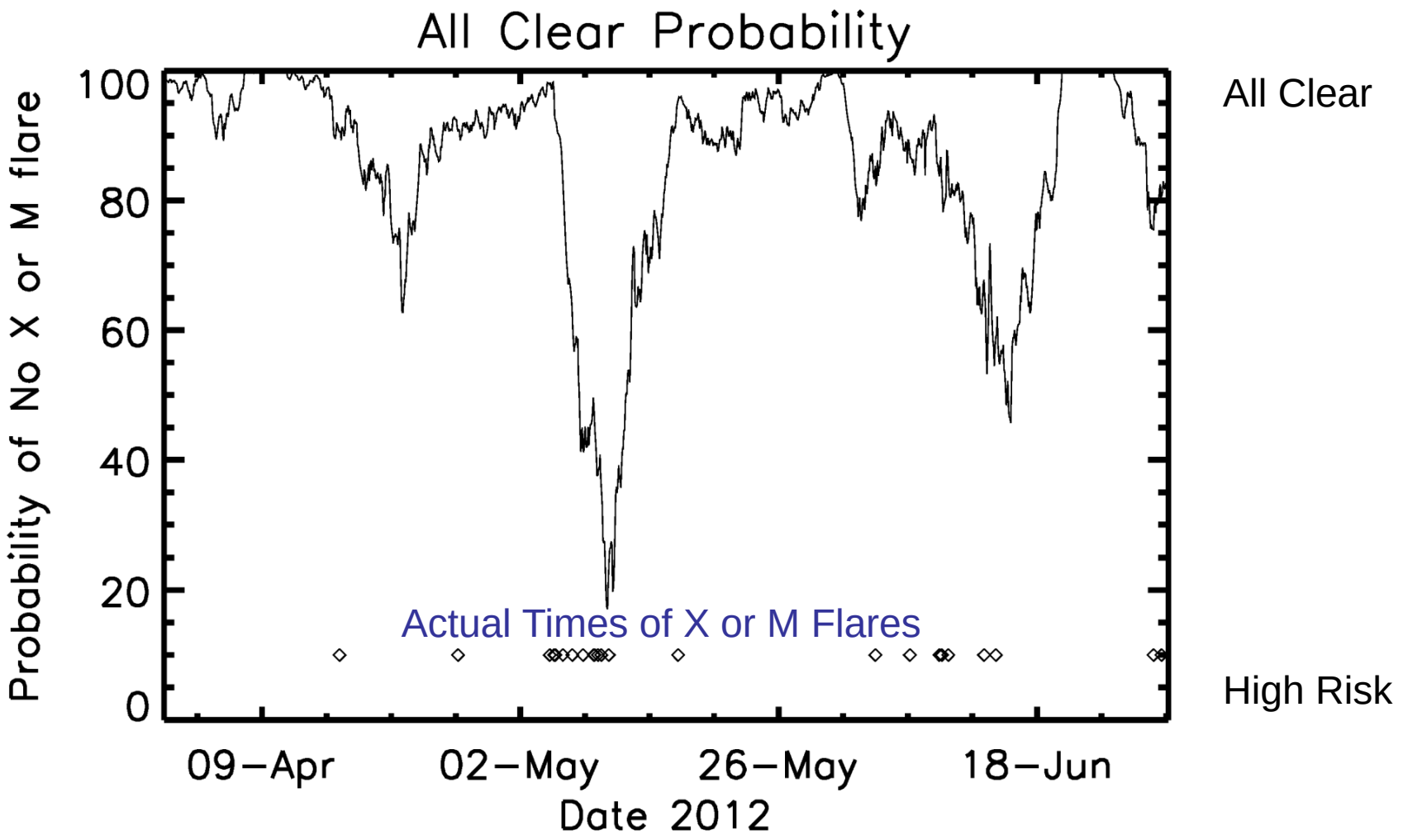




Active regions that have recently produced an X- or M-Class flare are more likely to produce flares in the near future

Dangerous Time Periods Exist

Actual operational data from JSC/SRAG



Comparison Forecast of Safe and Dangerous Days

June 26, 2013

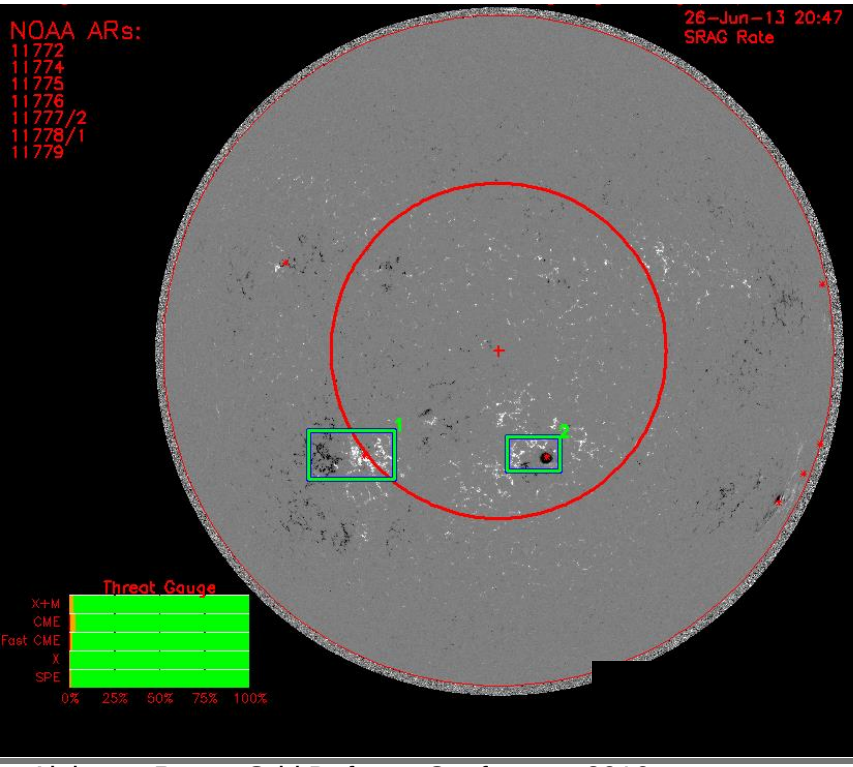
C1, C1.5 flares

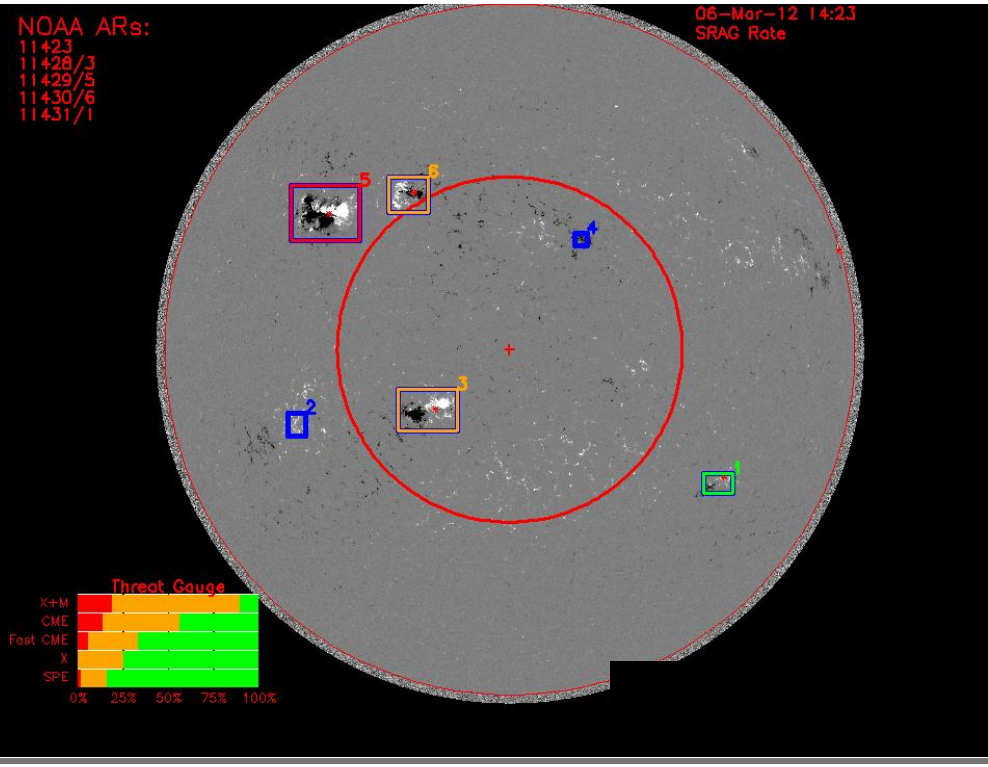
March 7, 2012

X5.4, X1.3, C1.6

CME 2684, 1825 km/sec,

Solar Energetic Proton Event reaches 6530 particle flux unit >10MeV



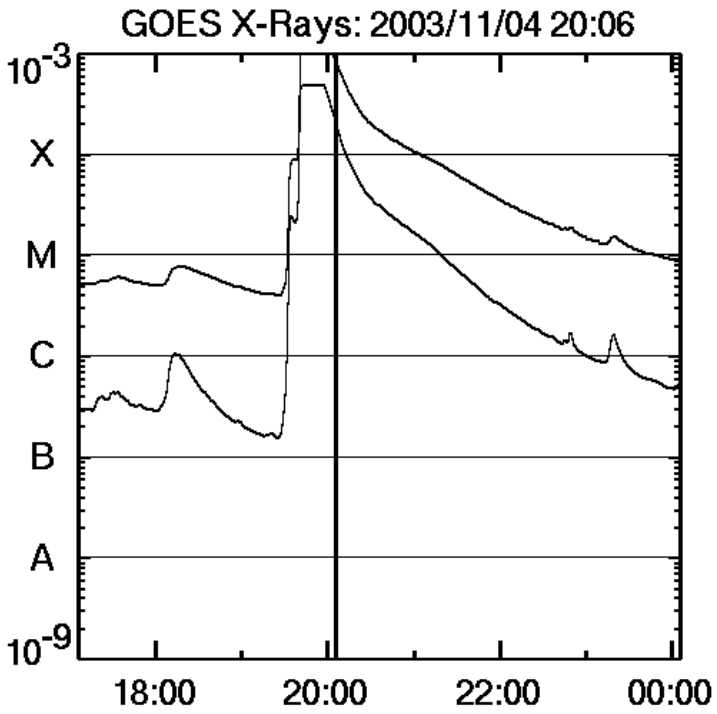


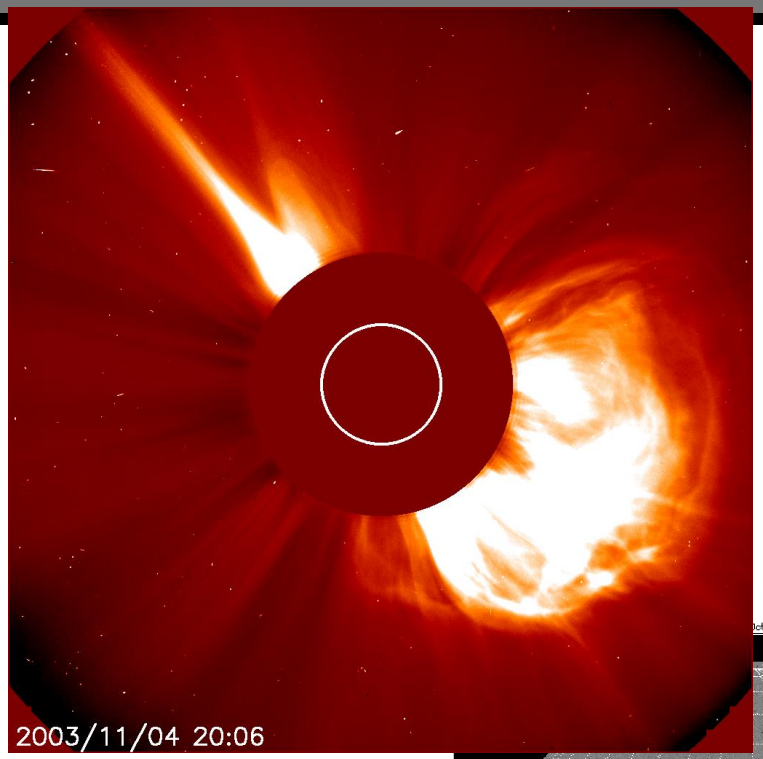
Conclusions

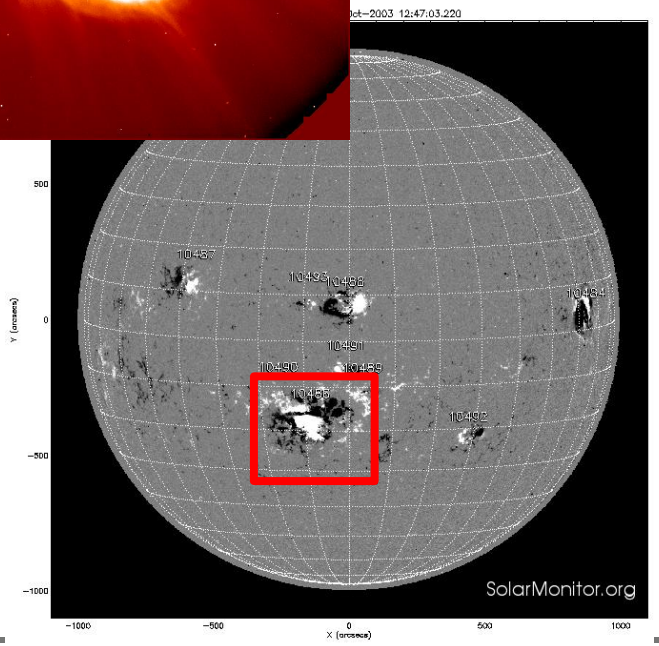
Forecasting CMEs is the first step to forecasting dangerous Geomagnetic Storms and possible threat to Alabama's Power Grid

- Geomagnetic Storm Watch: Dangerous active region is near disk center or approaching
- Warning: Fast, Earth-Directed CME has occurred, 1-4 day arrival time, the faster ones are the most dangerous
- ACE at L1, has determined that the CME has a southward B_z
- Need to know what level of event, timing and other factors will affect Alabama's Power grid (instead of New York's)
- Need a plan to minimize long-term damage
  - Safe Mode
  - Similar to tornado impact plan

End







- What if this happened 7 days earlier

Backup

Forecast Skill Score

Definitions

	Actual Yes	Actual No
Predict Yes	YY	YN
Predict No	NY	NN

Metric Equations

Percent Correct	PC=(YY+NN)/(YY+YN+NY+YY)
Probability of Detection	POD=YY/(YY+NY)
False Alarm Rate	FAR=YN/(YY+YN)
Heidke Skill Score	HSS=2*(YY*NN-YN*NY)/[(YY+NY)*(NY+NN)+(YY+YN)*(YN+NN)]
True Skill Score	TSS=(YY*NN-NY*YN)/((YY+NY)*(YN+NN))

Forecast Skill Scores

- Only 5% of the active regions produce a major flare in the next 24 hours, so Percent Correct Forecasts, will be high but misleading
- Probability of Detection is important, for big events did you forecast it. This is important.
- But if event rates are 50% chance per a day, for several days, to have a high probability of detection, you will have a higher false alarm rate.
- It is a matter of tradeoffs.

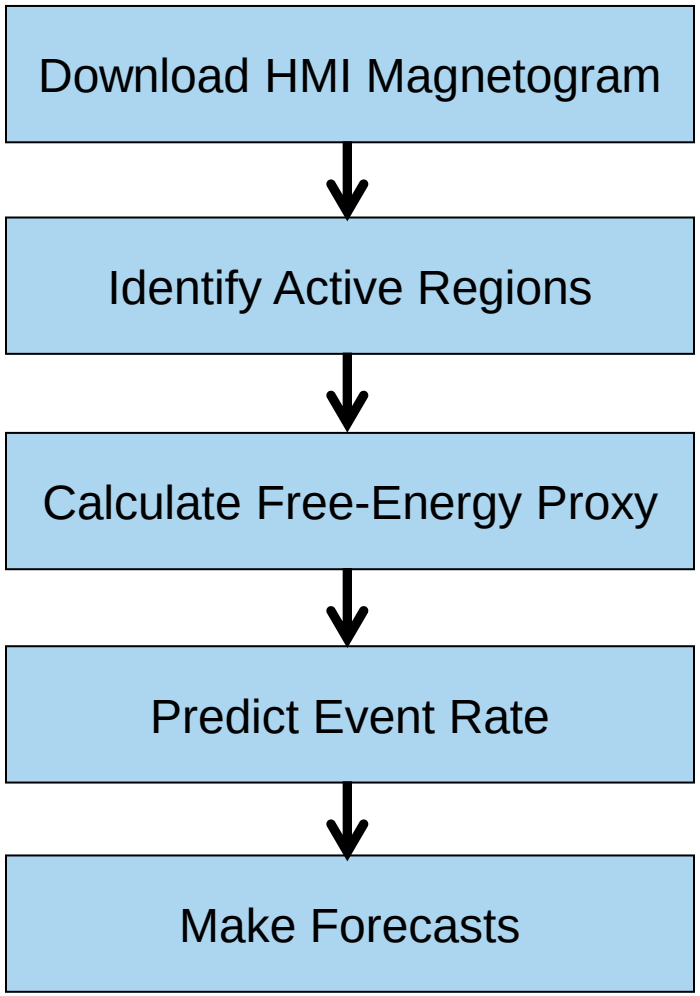
How Well Does MAG4 Forecast:

2. Skill Metrics Significance of Upgrade

Forecast Method	YY	YN	NY	NN	PC(%)	POD	FAR	HSS	TSS
McIntosh/**NOAA**	259	638	631	18476	93.7	0.29	0.71	0.26	0.26
Free-Energy Proxy **Present MAG4**	273	284	618	18830	95.5	0.31	0.50	0.35	0.47
Free-energy proxy and previous flare activity **Upgraded MAG4**	340	317	551	18797	**95.7**	**0.38**	**0.48**	**0.42**	**0.49**
Best	890	0	0	19114	100	1	0	1	1

Improvement in Metric	PC(%)	POD	FAR	HSS	TSS
McIntosh/**NOAA** **Present MAG4**	1.8±0.5 **(4σ)**	0.03±0.05 **(0.3σ)**	0.21±0.07 **(3σ)**	0.10±0.04 **(2σ)**	0.21±0.07 **(3σ)**
Present MAG4 **Upgraded MAG4**	0.2±0.2 **(0.7σ)**	0.08±0.03 **(2σ)**	0.02±0.05 **(0.5σ)**	0.06±0.03 **(2σ)**	0.03±0.05 **(0.5σ)**

MAG4 Automated Processes



MAG4 is completely automated, from downloading magnetograms to outputting and storing forecast products

MAG4 Research-to-Operations Timeline

- *2011* MAG4 installed at JSC Space Radiation Analysis Group (SRAG) as a NRT (Near-Real-Time) forecasting tool, and SRAG began pre-operations testing
- *2012* Provided NOAA web access to MAG4 NRT forecasts
- *2013* MAG4 upgraded so that it can use a combination **of free-energy proxy** and previous **flare activity, for better accuracy**
- *2013* Won the Silver Snoopy Award
- *2015* Transition from HMI line-of-sight magnetogram to vector magnetograms
- *2016* MSFC Software of the Year Award, Honorable Mention for NASA's

Silver Snoopy

"Employees must have significantly contributed to the human space flight program to ensure flight safety and mission success."

Free-Magnetic Energy

Contours Vertical Magnetic Field
Arrows Transverse Magnetic Field

Currents ~10^{12} Amps